Production and Analysis of GSWP-2 Near-Surface Meteorology Data Sets

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Abstract

The Second Global Soil Wetness Project (GSWP-2) encompasses the same core 10-year period as the International Satellite Land-Surface Climatology Project (ISLSCP) Initiative II (1986-1995). We have produced a complete set of 3-hourly near-surface meteorological data sets based on the reanalyses and gridded observational data used in ISLSCP Initiative II, and extended the data set back to July 1982 for the purpose of spinning up the participating land surface schemes in GSWP-2. The baseline fields are a hybrid of observations and reanalyses for most variables. Hybridization allows us to remove systematic errors in the reanalysis fields. We describe the methods of data hybridization and compare the different data sets. This documentation is intended to give GSWP-2 modelers and other users general information about the strengths and weaknesses of each data set, thereby helping the modelers to analyze and explain their results.

1. Introduction

The land surface component of the hydrological cycle is fundamental to the overall functioning of atmospheric and climate processes. In particular, soil wetness plays an important role in climate. Knowledge of the state of soil wetness may be essential for improving climate prediction on seasonal-to-interannual time scales (AMS Council, 2001). However, there are no long-term reliable observation-based global data sets for model initialization. The primary reason for this is that soil moisture is sparsely measured *in situ* and is not well estimated by satellite remote sensing, while it exhibits very large spatial and temporal variability. Similar problems exist for other land surface state variables, such as snow and soil temperature. The Global Soil Wetness Project (GSWP) is charged with producing, as a community effort, global estimates of soil moisture, temperature, snow water equivalent, and surface fluxes by integrating one-way uncoupled land surface schemes (LSSs) using externally specified near-surface meteorological forcings and standardized soil and vegetation distributions (International GEWEX Project Office, IGPO 2002).

For many years, the only sources of global gridded analyses of the near-surface state of the atmosphere were the operational analyses of the major national meteorological centers. These analyses are produced two to eight times per day by assimilating the most current set of atmospheric observations into a global circulation model of the atmosphere. These observations include regular weather reports in the form of surface station observations, radiosonde, aircraft and balloon measurements of the troposphere, and, in recent decades, satellite retrievals. While those analyses provided the best near-real-time estimates of the state of the atmosphere for purposes of initializing global weather forecast models, they are not ideal for applications such as GSWP. That is because the models used for assimilation and forecasting are constantly changing. Thus, long time series of operational analyses are full of discontinuities and other inconsistencies as the underlying model changed over time. Such time series cannot be used with confidence to assess interannual variability or climate change.

The solution to this problem is the production of retrospective analyses, called reanalyses – long-term analyses using a frozen modeling and assimilation framework (Bengtsson and Shukla 1988). Reanalyses have the added benefit of being able to assimilate additional data streams that are not normally available in near-real-time. Both the National Centers for Environmental

Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) have produced two global reanalyses spanning from 15 to more than 50 years, and other centers have produced additional reanalyses that are more limited in time or space.

While a vast improvement over operational analyses for long-term environmental research, the reanalysis products have their own problems. An important shortcoming is that the reanalyses strongly reflect the biases and errors in the underlying general circulation models (GCMs). These are most evident in the flux estimates, although they do appear in the state variables, particularly in regions that have little observational data input (Kalnay et al. 1996). A favorite solution to this problem is to combine the reanalysis estimates with global gridded data sets from observations, which are usually at a lower temporal resolution than the reanalysis, and most readily available for near-surface quantities such as temperature and precipitation. Typically, the time-averaged information from the observed data set is combined with the high-frequency variability information from the reanalysis to produce a data set with the full spatial and temporal coverage of the reanalysis, but with the systematic errors minimized. Such hybrid data sets contain the most useful elements of both data streams.

There have been several attempts to produce hybrid near-surface meteorological data sets for use in the land surface modeling community. Liston et al. (1993) hybridized precipitation using a 10-year gridded monthly observational data set disaggregated to daily time scales using storm frequency information from the First GARP Global Experiment year of 1979. A similar procedure was used to produce the six-hourly precipitation data for the International Satellite Land Surface Climatology Project (ISLSCP) Initiative I data set for 1987-1988 (Meeson et al. 1995), using the NCEP/National Center for Atmospheric Research (NCAR) reanalysis estimates of precipitation (Kalnay et al. 1996). Downward surface radiation data were also hybridized in the ISLSCP Initiative I data set from ECMWF operational analyses (Sellers et al. 1996). The ISLSCP Initiative I data were used as an upper boundary forcing for the LSSs in the pilot phase of GSWP (Dirmeyer et al. 1999). Schnur and Lettenmaier (1997) extended the hybridization process to near-surface air temperature for their 15-year daily global estimates of soil moisture. Dirmeyer and Tan (2001) applied hybridization to temperature, precipitation and radiation in the production of a 21-year (24 including spin-up period) 6-hourly meteorological data set based on the NCEP/NCAR reanalysis (Kalnay et al. 1996). Berg et al. (2003) applied corrections to both ECMWF and NCEP/NCAR reanalyses and specifically examined the impact of bias correction on the LSS simulations, finding benefits in terms of reduced errors in surface hydrologic quantities over North America.

Land Data Assimilation Systems (LDAS) being developed by NCEP and the National Aeronautics and Space Administration (NASA), among others, make use of various satellite and ground-based observation systems within a land data assimilation framework, in order to produce optimal output fields of land surface states and fluxes (Cosgrove et al. 2003). However, these efforts are only beginning to reach a mature, operational state.

ISLSCP recently undertook Initiative II to produce a ten-year gridded global surface data set (Hall et al. 2003). The data set includes near-surface meteorology at a 3-hourly interval from the latest reanalysis products from NCEP/DOE and ECMWF, the NCEP/Department of Energy (DOE) reanalysis (Kanamitsu et al. 2002), and the ECMWF 40-year re-analysis (ERA-40; Simmons and Gibson 2000, Betts and Beljaars 2003). However, the reanalysis products are offered by ISLSCP Initiative II without any bias correction.

One of the goals of GSWP is to provide a large-scale validation and quality check of the ISLSCP data sets. GSWP-2 encompasses the same core 10-year period as ISLSCP Initiative II (1986-1995). However, another goal of GSWP is to provide the best global estimates of land surface state variables and fluxes. Since the reanalysis products contain some systematic errors compared to observation data, the meteorological forcing data from ISLSCP-II are not optimal for the GSWP-2 baseline simulation. The time resolution for available gridded observational data in the ISLSCP Initiative II data set is normally monthly, making it ideal for use in a hybridization procedure with the reanalysis estimates. In Section 2, we first describe the general pre-processing for all variables, and then describe the different calculation methods for each variable in detail. In Section 3, we show the results for the GSWP-2 products. Finally, a summary is presented.

2. Data process methods

2.1 General pre-processing

The Center for Ocean-Land Atmosphere Studies (COLA) produced the near-surface data set for ISLSCP-II from the NCEP/DOE reanalysis (Kanamitsu et al. 2002). The purpose of the NCEP/DOE reanalysis is to provide an improved version of the original NCEP/NCAR reanalysis

(Kalnay et al. 1996; Kistler et al. 2001) for use by the Atmospheric Model Inter-comparison Project (AMIP) II (Gleckler 1996) for GCM validation. The NCEP/DOE reanalysis uses a similar analysis system to the NCEP/NCAR reanalysis and an upgraded version of the same general circulation model, with known errors from the NCEP/NCAR reanalysis procedure fixed and assimilation of a more complete stream of observational data after 1993 (Kanamitsu et al. 2002). Two types of variables exist in this data: instantaneous fields (primarily state variables), and average fields (primarily flux fields expressed as a rate). The 3-hourly near-surface meteorological data provided in ISLSCP Initiative II are pure reanalysis products, and have not been amended by "hybridizing" with observational data, as was done for ISLSCP Initiative I.

Near-surface meteorological state variables and fluxes from the NCEP/DOE reanalysis are of potentially great value to the ISLSCP data user community. To co-register the NCEP/DOE reanalysis on the ISLSCP 1° grid, the reanalysis data set was regridded from its native T62 (Gaussian grid) resolution (192 x 94 grid boxes globally) to 1° ISLSCP-II required resolution and processed from hourly data to 3-hourly data. Data on the T62 NCEP/DOE model grid have been interpolated to the ISLSCP 1° x 1° grid, as consistently as possible with the land-sea mask definitions of each grid. The NCEP/DOE land-sea mask and the ISLSCP land-sea mask are used to ensure that land points are transformed into land points and sea points are used for sea points. For every grid box on the target ISLSCP grid, there are from one to four overlapping grid boxes of the input NCEP/DOE grid; only those points are selected that are of the same type as the target grid point (sea for sea and land for land). No distinction is made over land between permanent ice and ice-free grid points. All intersecting grid boxes of same type are used to perform a bi-linear interpolation of the data. If none of the intersecting grid boxes have the same type, they are all used for bi-linear interpolation. This may occur at locations where, for instance, the ISLSCP mask has a lake, whereas the NCEP/DOE mask has only land points in the surroundings. In this case, the consistency between land sea masks is lost. Figure 1 shows the consistency between the two masks. Grid boxes are shaded red where ISLSCP-II has land but NCEP/DOE has water, and green shading indicates where ISLSCP-II has water but NCEP/DOE has land.

The default meteorological forcing data set for GSWP-2 is based on the ISLSCP Initiative II regridding of the NCEP/DOE reanalysis of 1986-1995. Only land surface points are retained, and Antarctica is omitted from the analysis. Corrections to the systematic biases in the reanalysis fields are made by hybridization of the 3-hourly analysis with global observationally-based gridded data sets at a lower temporal resolution. This means that the atmospheric forcing data uses information from global gridded observational data sets when possible. In some cases, no adequate global observational data exist, so a pure model reanalysis product is used. In most cases, observational data are available globally, but not at the high time resolution needed to resolve the diurnal cycle, as is necessary to force LSSs. In these instances, observational data is combined with data from model-based reanalysis products. The monthly means of the hybrid products would be the same as observed data, but the different reanalyses would likely exhibit somewhat different characters in the diurnal cycle and synoptic variability, which could influence the simulation of the surface energy and water balances in offline LSS simulations.

The hybridization process has been developed, tested, applied, and documented for the NCEP/NCAR reanalysis data (Dirmeyer and Tan 2001), and can be applied to the other reanalysis products. Because the full 10-year span of the NCEP/DOE reanalysis data was available before ECMWF’s reanalysis, the hybridized version of the NCEP/DOE data set was chosen for the baseline simulation by the LSSs.

To facilitate the exchange of forcing data for land-surface schemes and the results produced by these schemes, the GEWEX (Global Energy and Water Cycle Experiment) Global Land-Atmosphere System Study (GLASS) established standards for LSS input and output called ALMA (Assistance for Land-surface Modeling Activities). The aim is to have a data exchange format which is stable but still general and flexible enough to evolve with the needs of LSSs. This should ensure that for each model, the implementation of procedures to exchange data needs to be done only once, and future inter-comparisons of land-surface schemes can be conducted more efficiently. The data format choices described here for ALMA are similar to the ones which were made by AMIP for collection data from GCMs. This ensures that the proposed data format is applicable for off-line land-surface simulations as well as coupled experiments and will thus be suited for all actions of GLASS. More information on ALMA is available online at: http://www.lmd.jussieu.fr/ALMA/.

2.2 Precipitation

Global observational data sets of quantities such as precipitation are probably superior to reanalysis estimates of precipitation, but they are far from perfect. Incomplete gauge coverage, difficulty in collecting observational data, national variations in instruments and calibration, and problems with the instruments themselves can lead to very uneven coverage and quality of observational data. Oki et al. (1999) showed in the pilot phase of GSWP LSS that runoff was systematically underestimated over high latitudes where snow is a significant contributor to annual precipitation. Motoya et al. (2003) has examined this issue in detail and provided an algorithm for gauge correction for wind-caused undercatch (which varies geographically depending on national instrument characteristics) that is being applied in GSWP-2. The precipitation product for the baseline simulations in GSWP-2 is a hybrid product of reanalysis, observations, and empirical corrections. In the hybridization process for precipitation and radiation, the reanalysis systematic errors are removed via a multiplicative scaling factor that is based on the ratio of observed monthly rainfall to reanalysis estimates, rather than by subtraction of the error:

$$[P]_{Y,M,D,T} = \frac{[\;OBS\;]_M}{[P_{NCEP}]_M}[P_{NCEP}]_{Y,M,D,T} \quad (1)$$

To get the adjusted forcing data for precipitation, for instance, the value at a grid box of one of the reanalysis precipitation terms (total or convective) at a given year (Y), month (M), day(D) and 3-hour time interval (T) is scaled by the ratio of the monthly mean observed precipitation to the corresponding mean value from the reanalysis for that month. This approach avoids problems of negative values in positive definite quantities with frequent zeroes, such as precipitation. It provides the best attainable improvement in the reanalysis estimates given the lack of a long-term sub-monthly global observationally-based data set.

No attempt is made to adjust the monthly storm frequency (Liston et al. 1993), as was done for the 6-hourly precipitation estimates in the ISLSCP Initiative I data set (Mitchell and Lin 1994). Nor is any attempt made to adjust the diurnal cycle, which is known to be in error over many regions. The main constraint is that the monthly mean precipitation should agree with the observation data, with some small differences introduced as a result of spatial interpolation. This preservation of observed monthly means is also in effect for all other hybridized variables.

Several observational precipitation data sets will be available from ISLSCP-II. The Climate Research Unit (CRU) (New et al. 1999; 2000) data set from University of East Anglia is a high-resolution (0.5°) gauge-only product, but relies on only operational data sources, does not correct for gauge undercatch, and relaxes the data to a mean annual cycle climatology when *in situ* data are scarce. The Global Precipitation Climatology Centre (GPCC) (Rudolf et al. 1994) maintains a gridded gauge analysis that contains more stations than the CRU analysis; these data are also provided to ISLSCP-II on a 0.5° grid. They do provide a separate monthly climatological correction factor to adjust for wind-caused gauge undercatch. The Global Precipitation Climatology Project (GPCP) (Huffman et al. 1997) also provides monthly analyses, which blend corrected gauge and satellite estimates. This data set may prove to be the best for interannually-varying precipitation data, but it has the lowest native spatial resolution (2.5°), although a 1° version is provided to ISLSCP-II. GSWP-2 will use NCEP/DOE hybrid with GPCC gauge data for the baseline period (1986-1995), and CRU for the spin-up period (July 1982 – December 1985; GPCC data is not available), applying the gauge correction of Motoya et al. (2003) from source code supplied by the author. Where the gauge density is low (see Figure 2 as an example, gauge density is variant with time), the GPCP product is blended in. In this way, gauge correction can be applied at a higher spatial resolution, while maintaining the benefit of satellite data where there are no gauges. The next step is hybridization with the reanalysis rainfall estimates, as described above, to produce a 3-hourly precipitation product from GPCC, GPCP and CRU data, which can then be combined and blended to produce the final product.

The process is as follows. Aggregated monthly GPCC, or CRU data are calculated, transforming from 0.5° to 1° (the GPCP data provided by ISLSCP Initiative II is available at 1°). Due to wind-caused gauge undercatch for precipitation, the Motoya et al. (2003) wind correction is applied to the unadjusted GPCC or CRU data, based on the reanalysis 10 meter wind speed. First, an "uncorrected gauge" for the reanalysis precipitation is estimated based on the catch ratio (C_R) correction factor calculated by the Motoya algorithm using the daily mean reanalysis wind:

$$P_{NCEP\_gauge} = \frac{NCEP}{C_R} \tag{2}$$

This is necessary because the precipitation as estimated by the analysis model is unaffected by wind, so the corresponding undercatch error must be introduced into the model estimate before adjustment. This step ensures that the final wind-corrected precipitation estimates maintain the same relative storm-to-storm totals as the NCEP/DOE reanalysis.

Secondly, we hybridize this "NCEP/DOE gauge" with GPCC or CRU gauge data as indicated in equation (1), so that the monthly total agrees with the uncorrected gauge data. Then we reapply Motoya's wind correction to the hybrid data:

$$P_{Wind\_corrected} = C_R P_{Hybrid\_uncorrected} \tag{3}$$

In regions of low gauge density, this result is combined with the hybridized 3-hourly version of the GPCP data:

$$P_{GSWP2} = aP_{Wind\_corrected} + (1-a)P_{Hybrid\_GPCP} \tag{4}$$

where

$$\begin{aligned} a &= 1, && \text{GPCC or CRU gauge density} = 2 \\ a &= 0.5, && \text{GPCC or CRU gauge density} = 1 \\ a &= 0, && \text{GPCC or CRU gauge density} = 0 \end{aligned} \tag{5}$$

The final step is the separation of the precipitation components into rainfall and snowfall, convective and large-scale. The NCEP/DOE reanalysis reports total precipitation rate, as well as a snowfall rate that is diagnosed at each model time step from the 850 hPa air temperature (or lowest model air layer temperature if the surface pressure at a given grid point is lower than 850 hPa). If this temperature is equal to or less than 0.0 ^{o}C, then snowfall is designated; otherwise, rainfall is chosen (K. Mitchell, personal communication). Since the snowfall criterion is based on the atmospheric model state aloft, and not surface conditions, no re-estimation of snowfall will be conducted based on the hybrid near surface air temperature. Rainfall is assumed to be total precipitation minus snowfall; no account is made for hail, sleet, ice pellets or graupel. The NCEP/DOE reanalysis also reports a convective precipitation rate. For GSWP-2, to conform to ALMA standards, a convective rainfall rate is given where:

$$Rain_{Conv} = \frac{Conv}{P_{Total}}(P_{Total} - Snow) \tag{6}$$

Large-scale rain would be $Rain$ – $Rain_{Conv}$, and if necessary, convective snowfall can be estimated assuming the same ratio as for total precipitation in the equation above.

Some decisions had to be made where inconsistencies were apparent. For instance, in the bi-linear interpolation of the precipitation data from the reanalysis grid to the ISLSCP grid, there were instances near coastlines where the interpolated snowfall rate exceeded the total precipitation rate. In these cases, the rainfall rate was set to zero. During hybridization, there were instances where one but not both of the observed monthly precipitation or the reanalysis precipitation was equal to zero. In these situations, it was assumed that precipitation for the month was zero. Also, due to wind correction, instances occurred where the snowfall is greater than 0.0085 kg/m^2/s (the ALMA limit). In these cases, the rate was set to 0.0085 kg/m^2/s.

2.3 Temperature

There is also more than one choice for near-surface temperature observations, although only the CRU data set from University of East Anglia is included in ISLSCP Initiative II. The monthly CRU temperature data are calculated as anomalies from a 12-month climatology that is derived relative to a fixed elevation model at 0.5°. In order to make a consistent adjustment of near-surface air temperature to the ISLSCP grid, the CRU temperatures are corrected for the altitude difference between the CRU grid and the ISLSCP Initiative II mean altitude derived from the GTOPO30 (Geographical Topography data at 30') data set. First, the CRU elevation data are recreated by aggregating the GTOPO5 elevation data from 5' to 0.5°. The monthly CRU temperature data are then corrected to the ISLSCP-II elevation:

$$T_1 = T_{CRU} - \frac{6.5}{1000}(Z_{ISLSCP2} - Z_{CRU}) \quad (7)$$

The monthly CRU data are then aggregated from 0.5° to 1°, and hybridized with the 3-hourly NCEP/DOE reanalyses 2-meter air temperature data by correcting the differences of monthly diurnal range and mean:

$$T_{GSWP2} = d\,(T_{NCEP} - \overline{T_{NCEP}}) + T_1 \quad (8)$$

where:

$$d = \frac{D_{CRU}}{D_{NCEP}} \quad (9)$$

constrained so that:

$$0.5 = d = 2.0 \qquad (10)$$

D is the monthly mean diurnal range of the temperature, which is reported for the CRU data, and has been calculated from the original hourly data from the NCEP/DOE reanalyses. Limits are placed on the diurnal scaling factor d to prevent unreasonable extreme temperatures.

2.4 Surface Pressure

An altitude correction is applied to the surface pressure data, to adjust from the reanalysis model grid elevations to the ISLSCP Initiative II mean altitude:

$$P_{s\_corr} = P_{s\_NCEP}\, exp\left[-\frac{g}{R\overline{T}}(Z_{ISLSCP2} - Z_{NCEP})\right] \qquad (11)$$

Z_{NCEP} and $Z_{ISLSCP2}$ are the grid box mean altitudes for the reanalysis and ISLSCP Initiative II respectively, g is the acceleration due to gravity, and R is the gas constant. $\overline{T}$ is the mean temperature between the two altitudes, calculated using the same lapse rate used to adjust temperature:

$$\overline{T} = T_{GSWP2} - \frac{1}{2}\left[\frac{6.5}{1000}(Z_{ISLSCP2} - Z_{NCEP})\right] \qquad (12)$$

2.5 Specific Humidity

The adjustments to temperature and surface pressure also affect the estimated specific humidity. Thus, it is also necessary to adjust the estimates of near-surface specific humidity from the reanalysis to avoid incidents of super-saturation. This is done by assuming the same relative humidity (RH) before and after the corrections, and then adjusting the specific humidity accordingly to agree with the adjusted temperature. i.e.:

$$RH = \frac{Q_{\_before} * (0.622 - Q_{s\_before})}{Q_{s\_before} * (0.622 - Q_{\_before})} = \frac{Q_{\_after} * (0.622 - Q_{s\_after})}{Q_{s\_after} * (0.622 - Q_{\_after})} \qquad (13)$$

thus,

$$Q_{GSWP2} = \frac{0.622 * RH * Q_{s\_after}}{0.622 - Q_{s\_after} + RH * Q_{s\_after}} \qquad (14)$$

where Q is the specific humidity, Q_S is the saturation specific humidity. Also, in order to avoid RH > 100%, if $Q > Qs$, then $Q = min(Q, Qs)$.

2.6 Radiation

Three-hourly Surface Radiation Budget (SRB) data produced at NASA/Langley Research Center is available through ISLSCP Initiative II. However, SRB radiation data only cover the period from January 1986 - October 1995, and they are instantaneous fields. Therefore, we use different methods to process downward shortwave and longwave data in different time periods. To adjust downward radiation, the diurnal cycle is particularly important. Studies by Dirmeyer and Tan (2001) have shown that the radiation errors in the NCEP/NCAR reanalysis are very systematic from year to year, but vary substantially across both the seasonal and diurnal cycles. We create a hybrid radiation forcing data set from reanalysis estimates by removing the climatological monthly mean diurnal cycle systematic errors calculated from the SRB and reanalysis data over the period. Some decisions had to be made where SRB data are not available. For example, there are some "undetermined" points for high latitude bands where the solar zenith angle approaches 90° in shortwave data set. These have been arbitrarily set equal to a small value: 10 W/m^2. An artifact of the SRB data handling procedure is that shortwave radiation data are discontinuous between each month, i.e. there are data gaps at the start and end of each month (R. Pinker, personal communication). Thus, we must hybridize with NCEP/DOE reanalyses to create data for the missing points and unavailable time periods (the 1982-1985 spin-up period and November-December 1995).

When SRB data is available, they must be changed from instantaneous to time-averaged fields to be consistent with NCEP/DOE data. For shortwave data, we first calculate the effective solar footprints for shortwave (SW) data at time t and $t+3$ as well as for NCEP/DOE data at each 20-min model time step over the 3-hour averaging period. Then, we compute the correction factor to multiply with $(SW(t)+SW(t+3))/2$ to create an effective average equivalent (SW_{CSRB}) to the NCEP/DOE 3-hour average over ($t,t+3–dt$), where dt is the NCEP/DOE model time step. Since the correction factor is a ratio, it is limited (from 0.5 to 2) to avoid the extreme values (e.g., SW_{CSRB} > 1360 W/m^2). For longwave (LW) data, we simply average SRB $LW(t)$ and $LW(t+3)$ to create the new LW_{CSRB} data.

As with precipitation, when SRB data are missing or not available, a multiplicative scaling is used to adjust the reanalysis. We calculated ten (January-October) or nine (November-December) years averaged monthly-3-hourly data from the newly created SW_{CSRB} and NCEP/DOE (not monthly mean in order to simulate the correct diurnal range), then hybridize with NCEP/DOE data as following:

$$[SW_{Hybrid}]_{Y,M,D,T} = \frac{[SW_{CSRB}]_{M-3-T}}{[SW_{NCEP}]_{M-3-T}}[SW_{NCEP}]_{Y,M,D,T} \tag{15}$$

During hybridization, there are instances where one but not both of the observed monthly-3-hourly shortwave radiation or the reanalysis radiation was equal to zero. In these situations, it is assumed that radiation was zero. The combined SW_{Hybrid} and SW_{CSRB} data is the final product for GSWP-2 baseline run. The same calculation is applied for longwave data.

2.7 Other Fields

The reanalysis wind products are used as is, with the 10 meter wind speed provided in the forcing data set.

All of the gridded surface characteristic data to be used by GSWP-2 have been converted to the ALMA data convention, including compression by gathering to reduce the data set sizes by removing ocean and land-ice points. Some extensions to ALMA have been recommended, especially concerning the formats for land surface properties, to create an updated ALMA version for GSWP-2. These include vegetation, soils, and topographic information at 1° resolution for all land points excluding Antarctica, essentially cutting off the global grid at 60°S.

3. Comparison of different products

3.1 Precipitation

Four precipitation products have been produced for the GSWP-2 baseline and sensitivity runs, which are:

(1) The original NCEP/DOE reanalysis data (as distributed as part of ISLSCP Initiative II);

(2) NCEP/DOE data hybridized with the GPCC (or CRU for spin-up period) data;

(3) product (2) with wind correction applied;

(4) product (3) combined with GPCP data where gauge density is low per equation (5) (this is for the GSWP-2 baseline run).

Recall that during the hybridization process, we assume the rate of monthly precipitation is zero where either the observed monthly precipitation or the reanalysis precipitation is equal to zero. Figure 3 shows the number of grid points and the median precipitation rate when the GPCC rate is greater than zero but NCEP/DOE is equal to zero. The number of points normally has a maximum value during boreal summer and minimum value in boreal winter. The points of this case occupy around 2.3% of the total 15238 points. The median precipitation rate at these points usually ranges from 0.25 to more than 2 mm/month. Thus, it appears that this assumption has a small, but perhaps non-trivial impact on global precipitation.

Figures 4 and 5 show for January and July respectively the 10-year average total precipitation rate (Figures 4a and 5a), convective rainfall rate (Figures 4b and 5b), and snowfall rate (Figures 4c and 5c) for the baseline precipitation product (4). In January, the snowfall is predominantly at mid- and high latitudes. The largest values are over Europe (especially Scandinavia), Canada and coastal Greenland. The convective rainfall is large over the tropics and the Southern Hemisphere. In July, the snowfall is limited over high latitudes and high-altitude areas. The large tropical convective rainfall belt moves to the north and increases in value at mid- and high latitudes with the seasonal change.

Figure 6 shows the difference of total precipitation rate between the baseline data set and the original NCEP/DOE estimates (i.e. product (4) minus (1)). During January, the total precipitation increases (mainly snowfall) are mostly over Europe, especially over Scandinavia. Also, rainfall increases over the middle of South America, Madagascar, and northern Australia. In contrast, precipitation decreases slightly over North America and China, due to NCEP/DOE overestimations compared to GPCC data. For convective rainfall, large decreases are found over the Andes, the eastern part of the Amazon, southern Africa and parts of Australia, due to NCEP/DOE overestimations. In July, total precipitation is significantly decreased over Thailand, southern India, Tibet Plateau, and Colombia, and slightly decreased over North America and Eurasia at high latitudes and east coast. The largest increases are over the Sahel region of Africa, Venezuela, northern India, Bangladesh, and Indonesia. The 10-year zonal monthly mean of total precipitation differences are shown stepwise between each product in Figure 7. Here the impacts of each hybridization step can be seen clearly. The GPCC hybrid with NCEP/DOE data (Figure 7c) shows that precipitation shows a general tendency toward a reduction in the summer season and an increase in winter compared to NCEP/DOE data, especially in the Southern Hemisphere mid-latitudes. The wind correction results in increases everywhere (Figure 7b), particularly during winter and in monsoon regions. However, due to blending with GPCP estimates in sparsely gauged regions, the final baseline somewhat compensates the wind correction where there are large adjustments in the wind correction product (Figure 7a). Overall, the baseline data might overestimate snowfall in Eurasia, rainfall in Congo, Sahara and Arabia, and underestimate rainfall in southern South America. The hybrid precipitation estimates produced for the spin-up period using CRU data have similar qualities to the GPCC hybrid data.

The large snowfall rates in coastal regions may be erroneously high due to the wind correction. In fact, there are instances where application of the upper ALMA limits on rainfall and snowfall rates result is a serious reduction in the calculated precipitation in some areas. Similarly, there is some evidence that the application of the GPCP precipitation estimates in gauge-poor regions may introduce unusual regional patterns of rainfall in some areas. In such areas, the locations of stations, or the gaps between stations, may show up as having drastically different rain rates than surrounding areas. For example, the heavy summertime rain rates over parts of West Africa appear to be due to GPCP overestimation of rainfall being applied in regions between gauges in the GPCC network.

3.2 Temperature

Figure 8 shows the 10-year average surface air temperature produced for the baseline GSWP-2 case for January and July. The monthly means reflect the CRU surface temperature, with a correction due to the differences in altitude between the CRU and ISLSCP data grids. Seasonality and fine-scale structure due to orography and the resolution of the data sets are apparent.

Figure 9 shows the difference of the GSWP-2 baseline product from the NCEP/DOE 2 meter air temperature estimates (i.e. NCEP/DOE hybrid with CRU data minus NCEP/DOE data) for January and July. In January, the temperature is reduced over northeastern Asia and northwestern

North America by 4 to 8 K, with some areas up to 12 K cooler. This appears to be a systematic bias over snow in the NCEP/DOE reanalysis. In contrast, from 50^{o}N to 20^{o}S and over the ice cap of Greenland the temperature is mainly increased, particularly over the Sahara, Tibet Plateau and Greenland. In July, the extreme magnitudes and the spatial scale of the areas of temperature change are decreased. Overall, the winter differences over Europe and Africa are related to the apparent errors in diurnal temperature range (Figure 10). The differences over western South America and Asia (Tibet Plateau) are mainly due to elevation correction (Figure 11). In Figure 10, it is shown that the CRU data, compared to NCEP/DOE reanalysis, have a smaller diurnal range over Europe and South America and a larger diurnal range over Africa, Asia, and southwestern Australia in January. In July, CRU data shows a smaller diurnal range over North America, much of the Amazon basin and monsoon Asia, and a larger diurnal range over southern Africa, much of Eurasia, and Australia.

There is some evidence that the adjustments applied to the diurnal temperature range may occasionally lead to unrealistically large swings in temperature over some regions, particularly very cold or very dry areas such as Greenland, the Sahara, and wintertime Central Asia. These swings produce obviously erroneously warm or cold readings in the temperature time series over some locations. This appears to be due to the fact that while the NCEP/DOE reanalysis largely underestimates the diurnal range in these areas, there are occasional limited periods of days or weeks where the reanalysis does a fairly good job, perhaps due to periods where systematic errors in clouds are absent. The scaling is calculated based on monthly statistics, and applied uniformly across each month. Thus, a scaling that generally corrects a problem in the diurnal cycle that is present, say, 80% of the time may drastically overcorrect during the other 20% of the time. Errors may also be introduced in other regions, in the form of a drastic reduction in the diurnal temperature range. Such errors are not so obvious as those that increase the extreme temperatures.

3.3 Surface pressure

Figure 12 shows the elevation difference between the ISLSCP-II and interpolated NCEP/DOE reanalysis orography data sets. This is used for the surface pressure correction in equation (11). The pattern of the correction looks somewhat different from the elevation correction for temperature (Figure 11). For temperature, the adjustment is from the mean station elevation to the ISLSCP-II orography, rather than from the reanalysis model orography.

3.4 Radiation

Figure 13 shows an example of the correction factor for changing SRB shortwave flux data from instantaneous to 3-hour time-averaged fields consistent with the other flux fields in the GSWP-2 forcing data set. This correction factor varies with Julian day and hour. The example shown is for a day in mid-January, and suggests how the overlapping footprints of consecutive 3-hour radiation estimates can be scaled to approximate a time-mean. The spatial pattern of this scaling factor is much smoother than the SRB fields with which it is multiplied – the SRB data include the effects of attenuation and scattering by clouds and aerosols.

Figures 14 and 15 show the 10-year average downward shortwave SRB data and the difference between SRB and NCEP/DOE reanalysis estimates in January and July. Compared to SRB data, NCEP/DOE data systematically overestimate downward shortwave radiation north of 30^{o}N, as well as over the Andes; but underestimates solar radiation in tropics, especially over the Amazon region, Sahara, Arabia, India, and Southeast Asia.

Figures 16 and 17 show the 10-year average downward longwave radiation from the SRB data and the difference between SRB and NCEP/DOE data in January and July. In January, NCEP/DOE overestimates downward longwave radiation over the northern Rocky Mountains and northern Asia; but underestimates over the Andes, Sahara, much of India, China, and southwestern Australia. In July, the NCEP/DOE reanalysis generally underestimates downwelling longwave radiation over most of the Northern Hemisphere and the Andes, especially over western North America, the Northern Sahara, the deserts of Asia, and Tibet Plateau.

4. Summary

GSWP-2 forcing data are a global gridded analysis series at 3-hourly time resolution and 1° spatial resolution from July 1982 through December 1995, which includes several versions of meteorological forcing fields for baseline simulations and sensitivity studies. The data are based on the NCEP/DOE reanalysis data as regridded as part of the ISLSCP Initiative II global data effort. These reanalysis data are hybridized with observed data (*in situ*, remote sensing, or a combination) in order to remove systematic errors that are found to exist in the reanalysis. The final product combines the high time resolution and complete spatial coverage of the reanalysis with the ground truth provided by the observational data sets.

There is evidence that while hybridization, scaling, and compositing of different climatological data sets may produce a global meteorological product that is better than any individual product, and certainly more suitable for the application of driving LSSs in uncoupled terrestrial climate simulations, the process is far from perfect. There are instances in this product where erroneous spatial or temporal variability appear to have been introduced during the hybridization process. Production of such data sets is an evolving science, and each attempt has been, and will likely continue to be, more sophisticated than the last. Short of a dense global observing network for near-surface meteorology capable of resolving the diurnal cycle, or global data assimilation models free of systematic errors, hybridization of model and observational data sets will remain the best means for producing accurate and complete gridded estimates of near-surface meteorlogical state variables and fluxes.

All of the data sets described here are available online through the GSWP web site at http://www.iges.org/gswp/.

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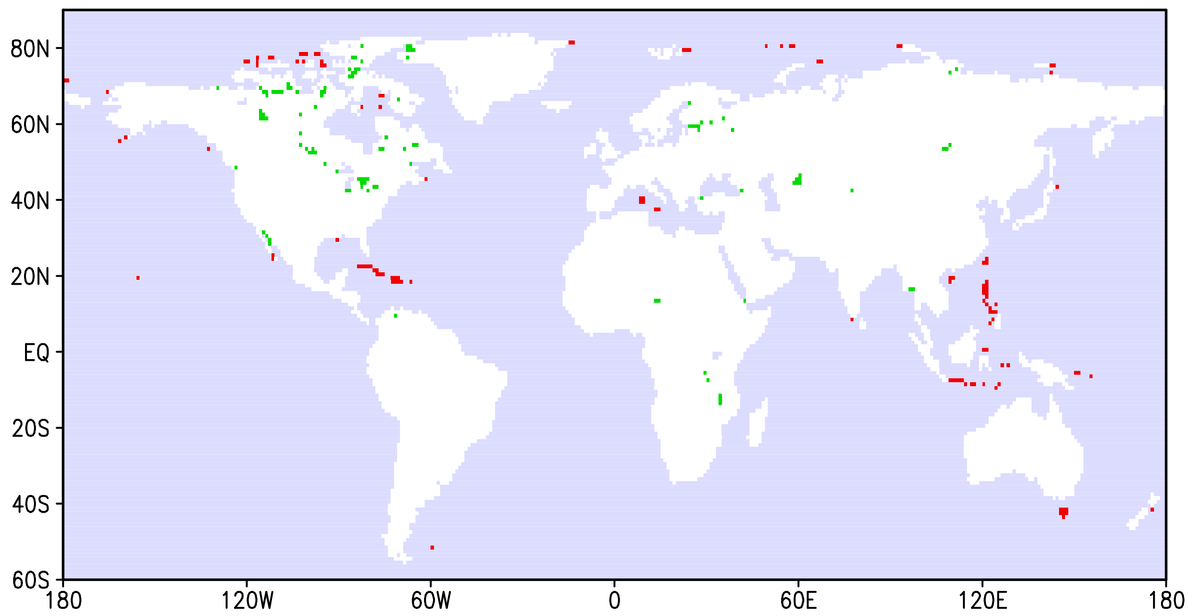

Figure 1 ISLSCP grid boxes where: ISLSCP is land but NCEP/DOE is water (red); ISLSCP is water, but NCEP/DOE is land (green).

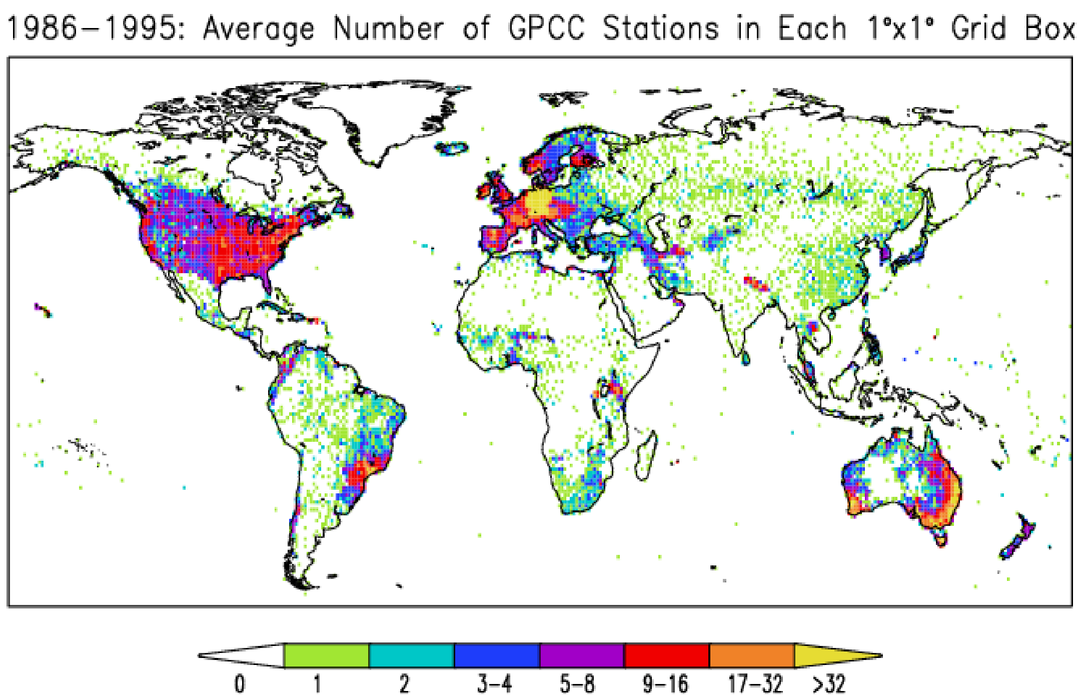

Figure 2 GPCC gauge density 10-year average number in each 1^{o} x 1^{o} grid box.

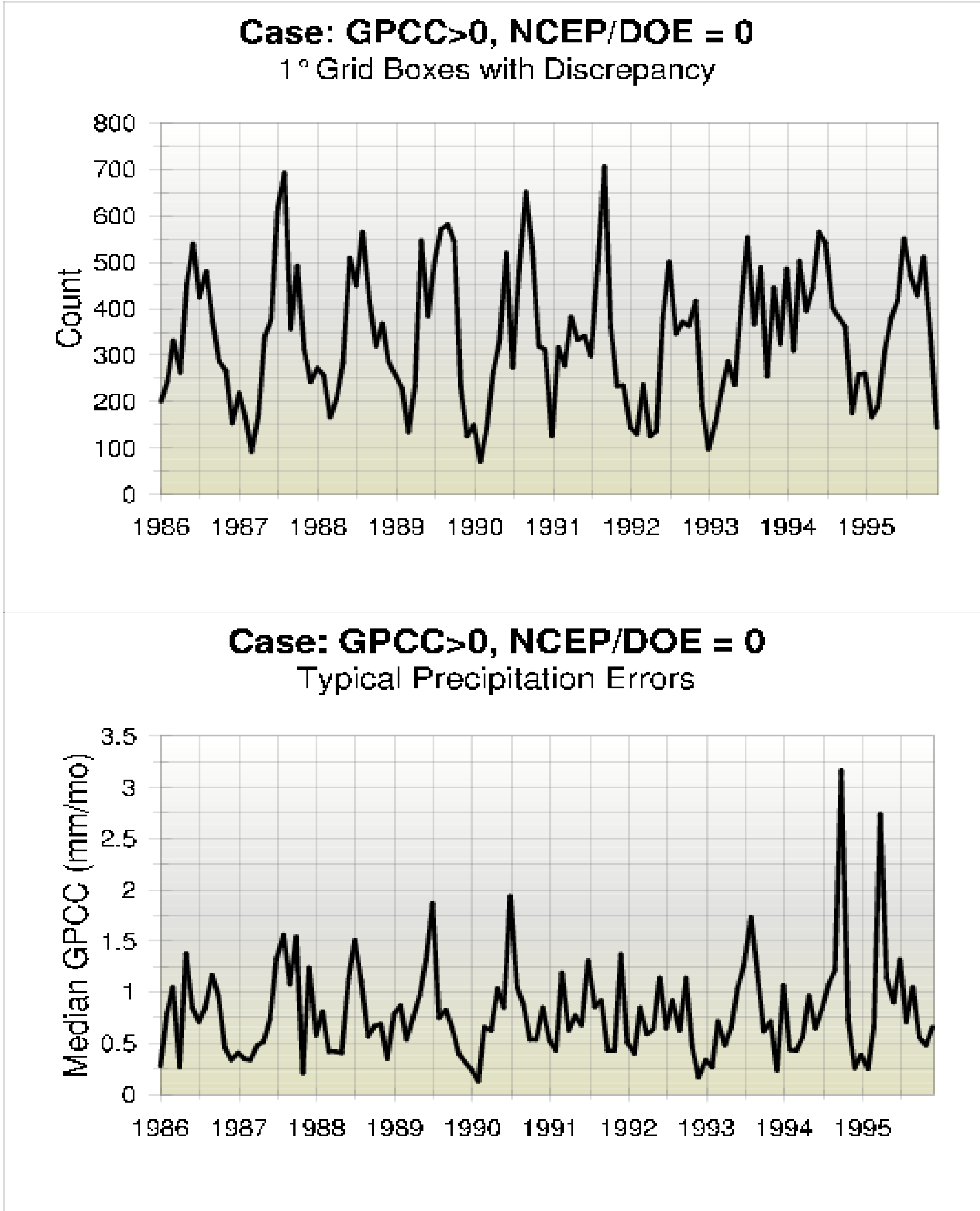

Figure 3 The monthly average (a) number of points and (b) median value for the case where GPCC data greater than zero, but NCEP/DOE data equal to zero.

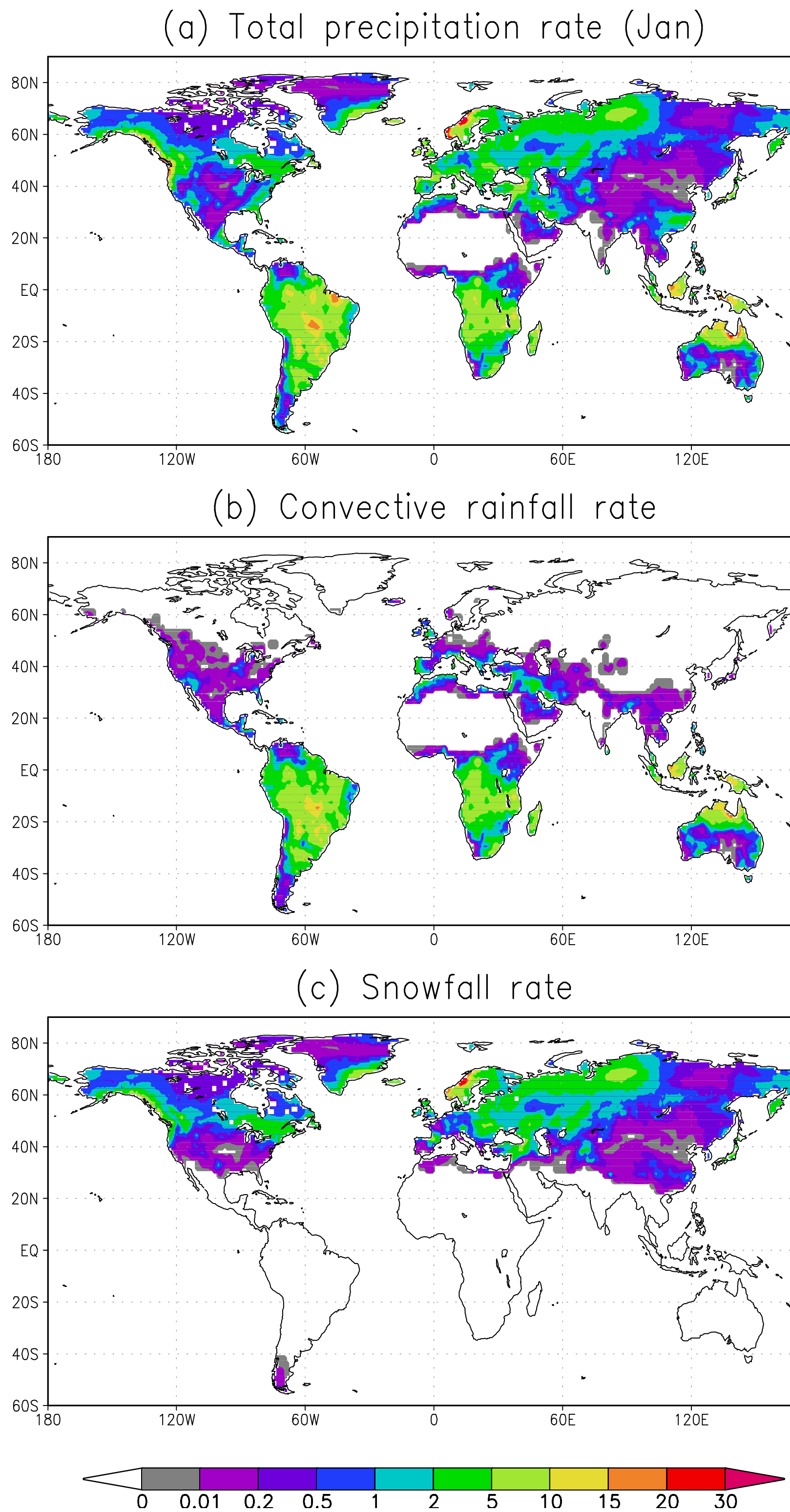

Figure 4 10-year average (a) total precipitation rate, (b) convective rainfall rate, and (c) snowfall rate for GSWP-2 baseline in January. Units are mm/day.

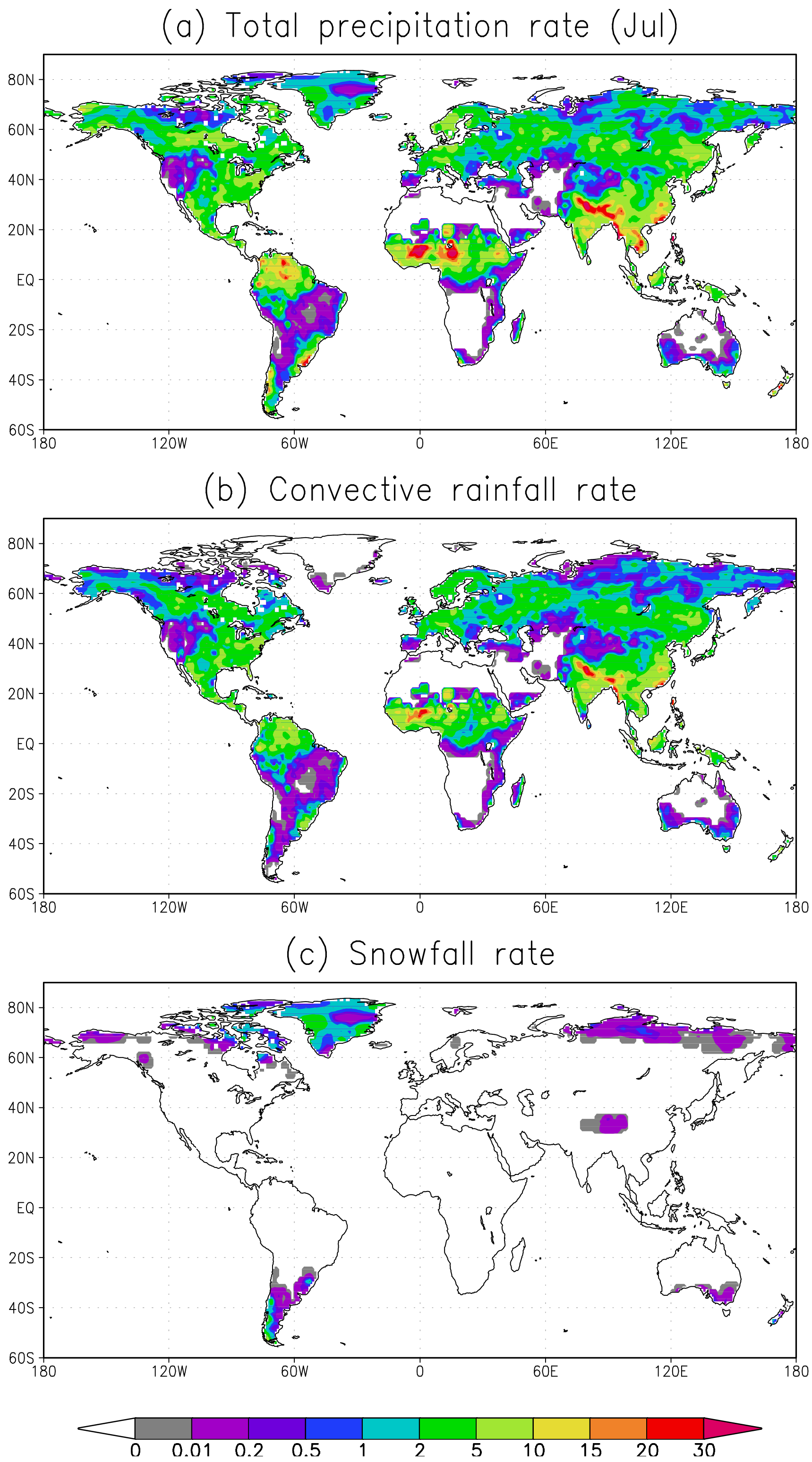

Figure 5 As in Figure 4, but for July.

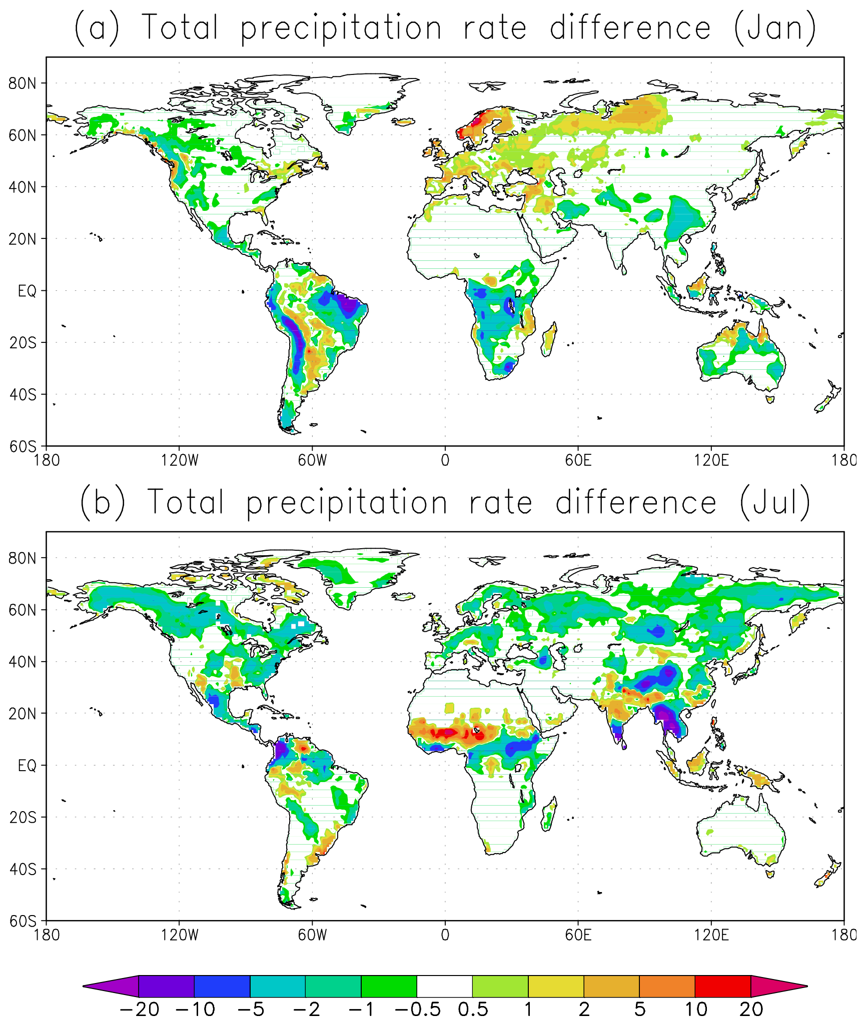

Figure 6 The difference of 10-year average total precipitation rate between GSWP-2 baseline and NCEP/DOE data in (a) January and (b) July. Units are mm/day.

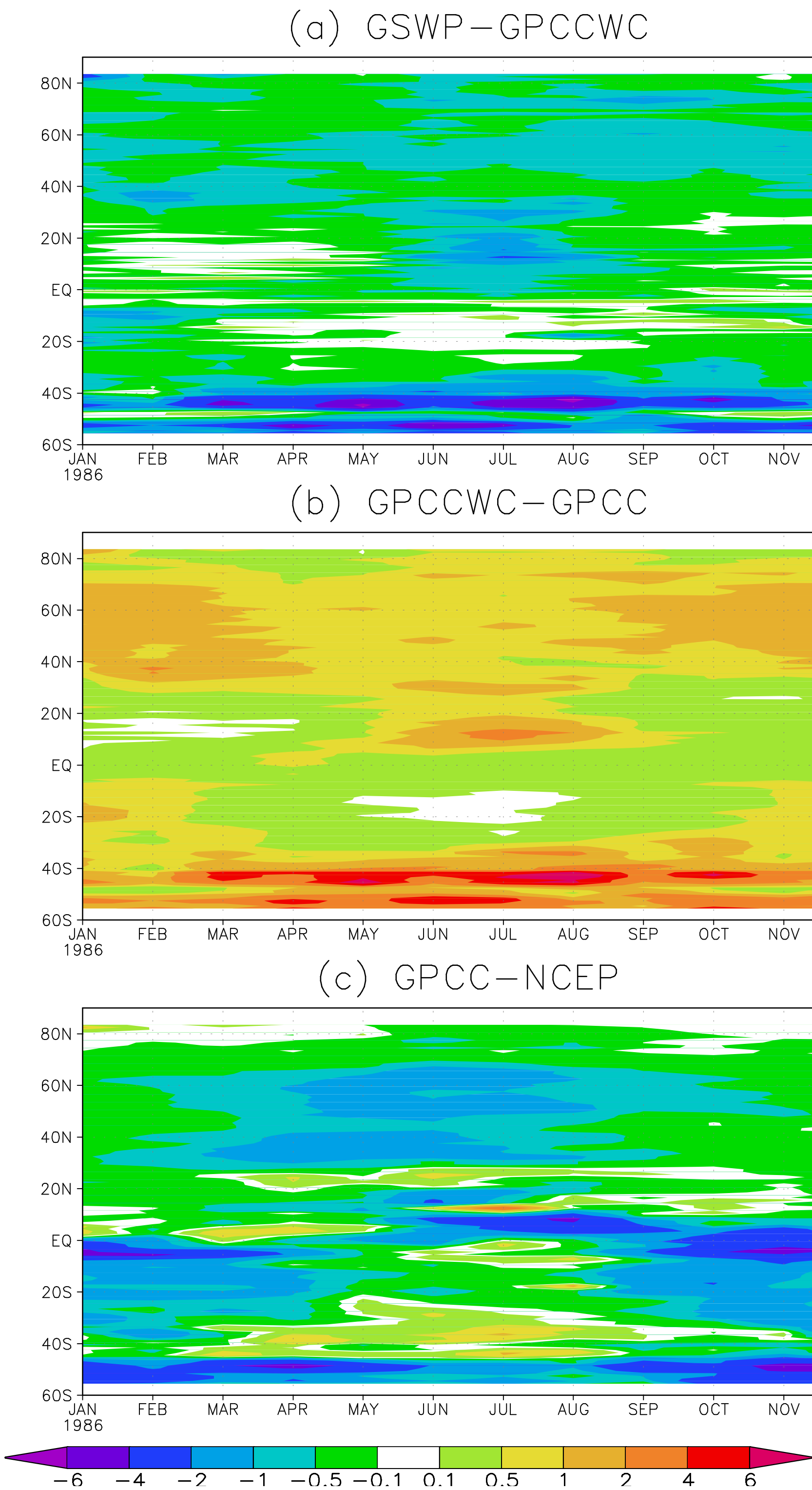

Figure 7 The difference of 10-year average zonal monthly mean of total precipitation rate, (a) GSWP-2 baseline minus GPCC hybrid with NCEP/DOE with wind correction, (b) GPCC hybrid with NCEP/DOE with wind correction minus GPCC hybrid with NCEP, and (c) GPCC hybrid with NCEP/DOE minus NCEP. Units are mm/day.

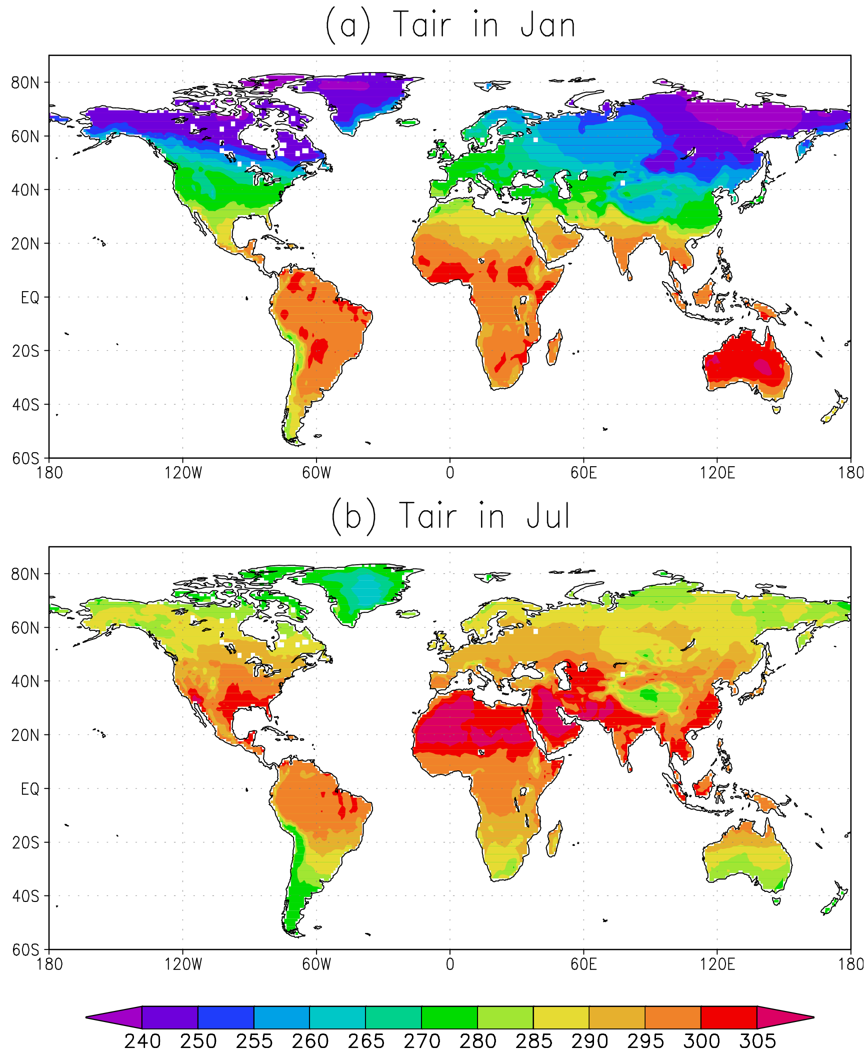

Figure 8 10-year average air temperature for the GSWP-2 baseline run in (a) January and (b) July. Units are K.

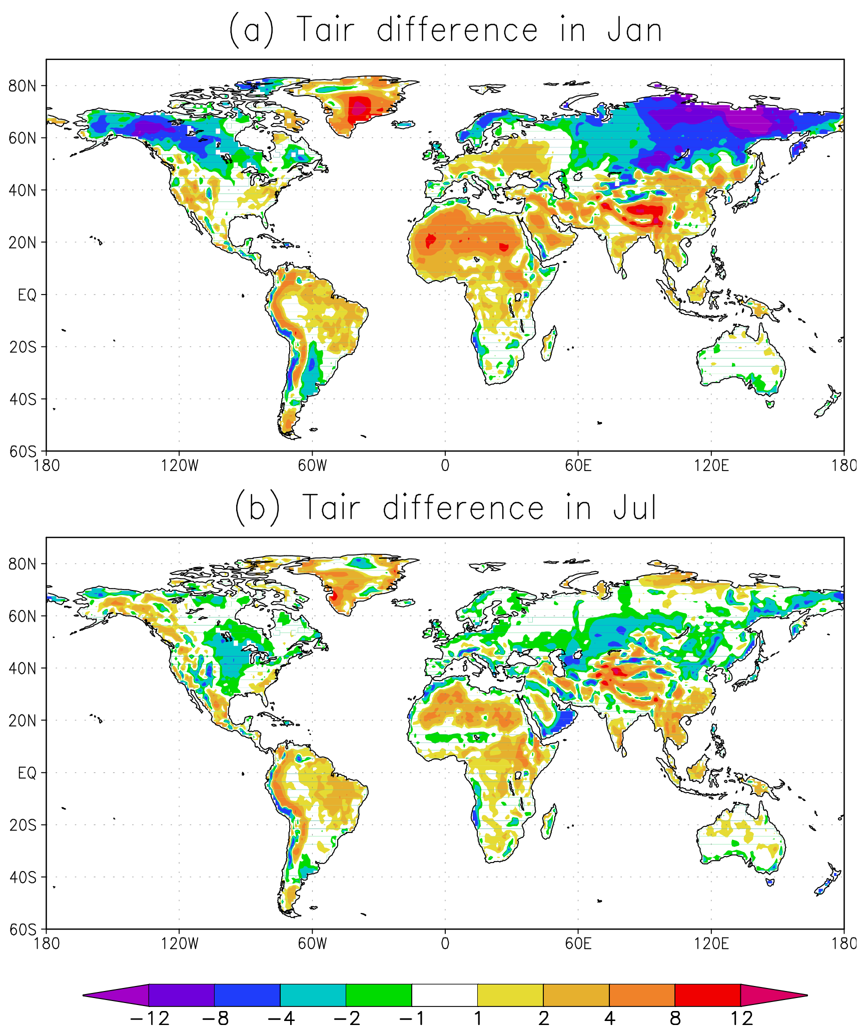

Figure 9 The difference of 10-year average air temperature between GSWP-2 baseline (CRU hybrid with NCEP) and NCEP/DOE data in (a) January and (b) July. Units are K.

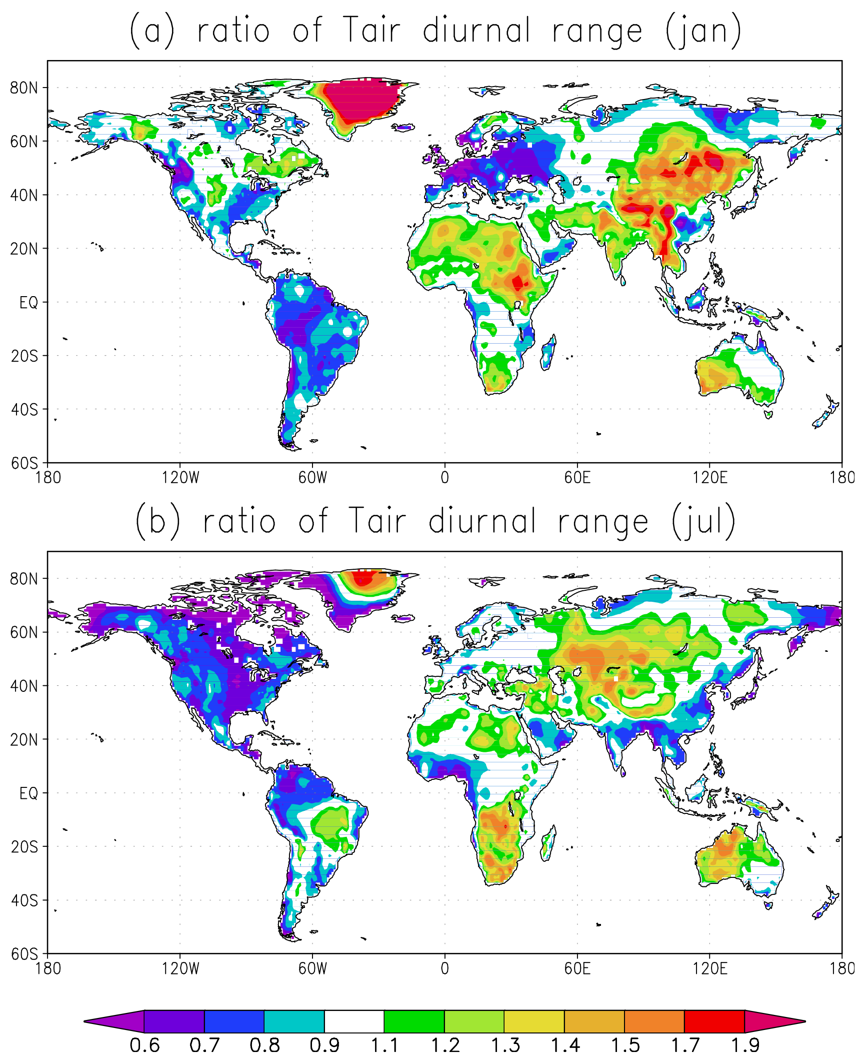

Figure 10 10-year average ratio of air temperature diurnal range between monthly CRU and NCEP/DOE data during (a) January and (b) July.

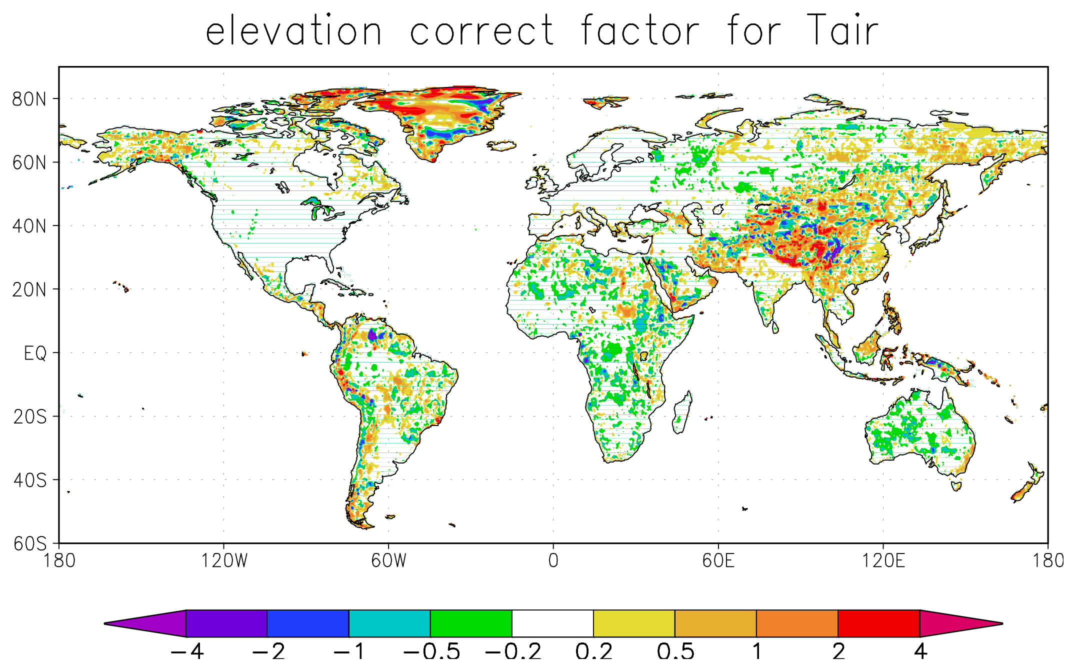

Figure 11 The elevation correct factor for air temperature. Unit is K.

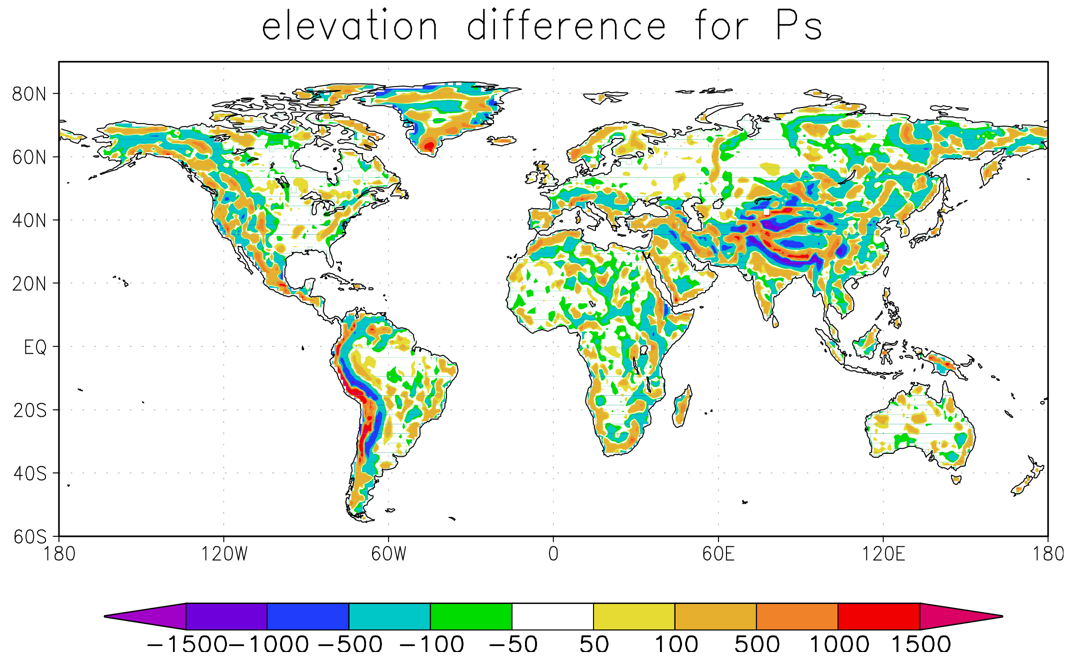

Figure 12 The elevation difference between ISLSCP-II and NCEP/DOE data for surface pressure correction. Unit is m.

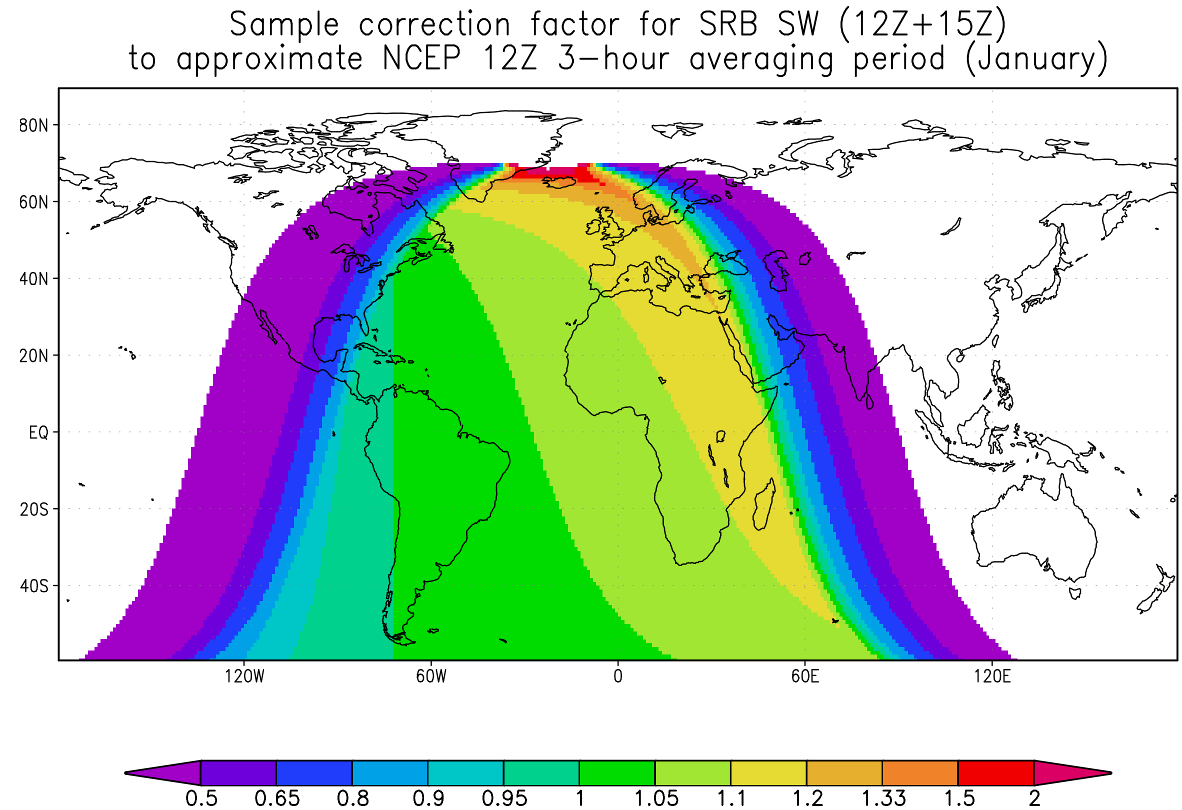

Figure 13 A sample of the correction factor for SRB shortwave radiation data for changing from instantaneous to 3-hour time-averaged fields.

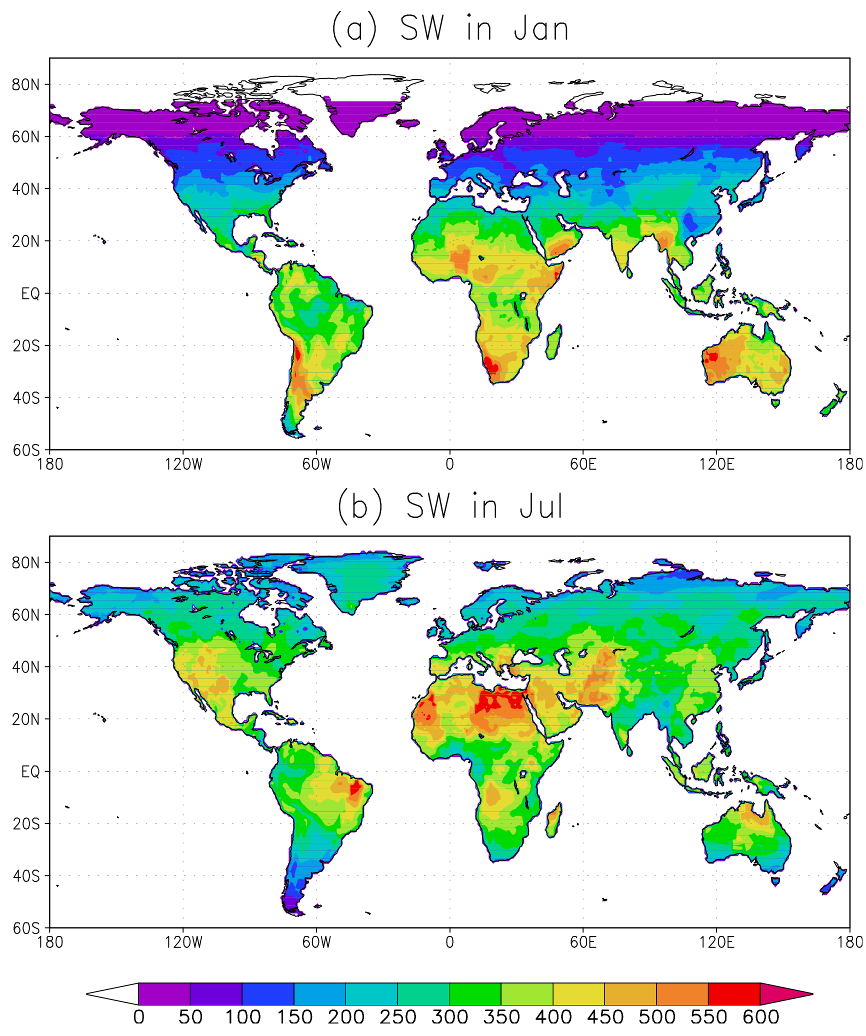

Figure 14 10-year average downward shortwave radiation data for baseline run in (a) January and (b) July. Units are W/m^2.

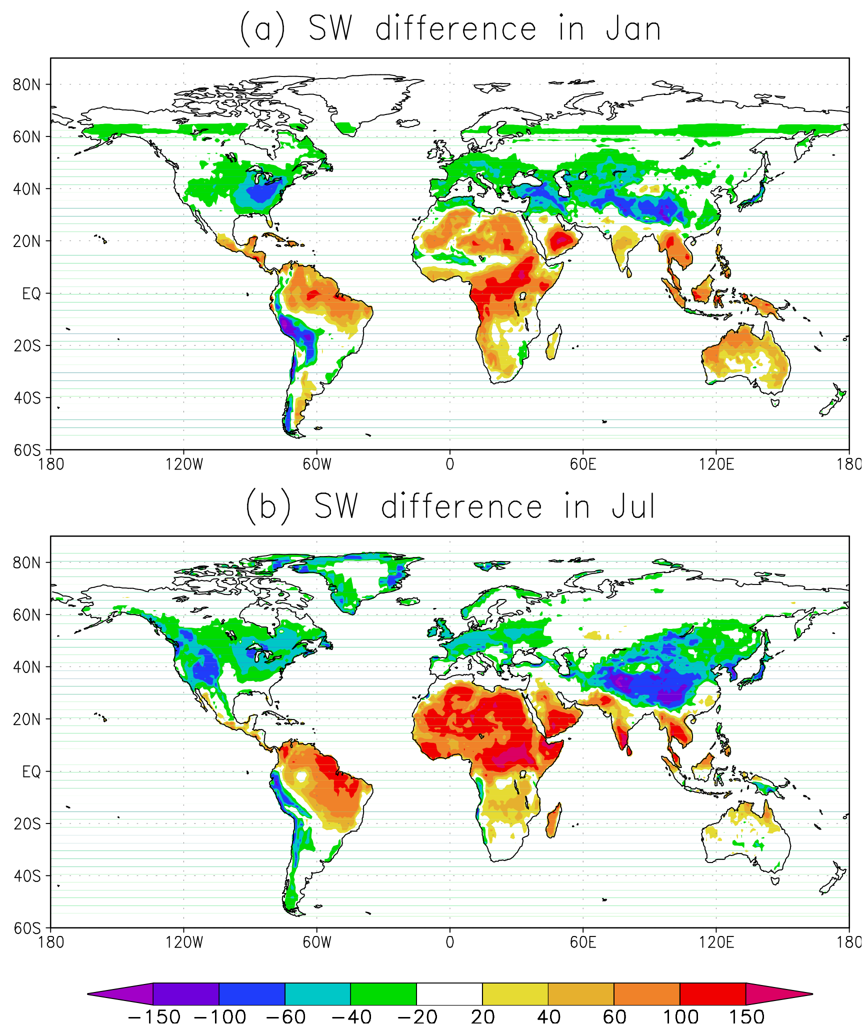

Figure 15 The difference of 10-year average downward shortwave radiation data between SRB and NCEP/DOE in (a) January and (b) July. Units are W/m^2.

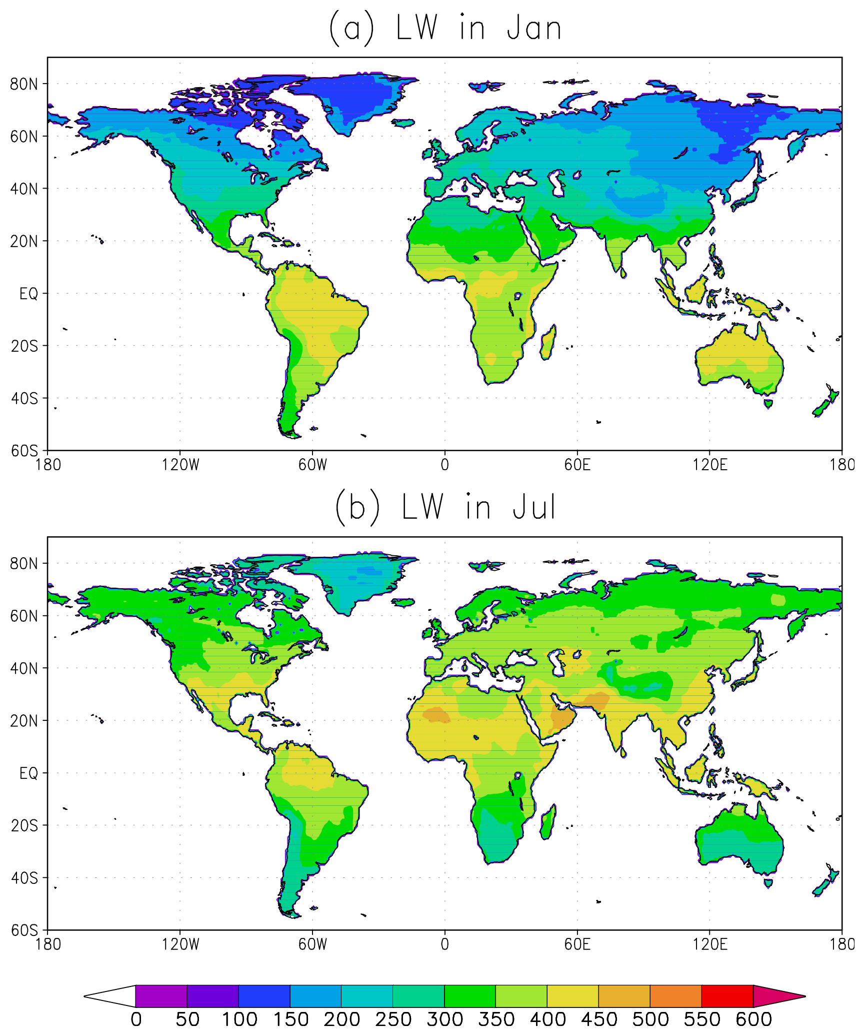

Figure 16 As in Figure 14, but for downward longwave radiation.

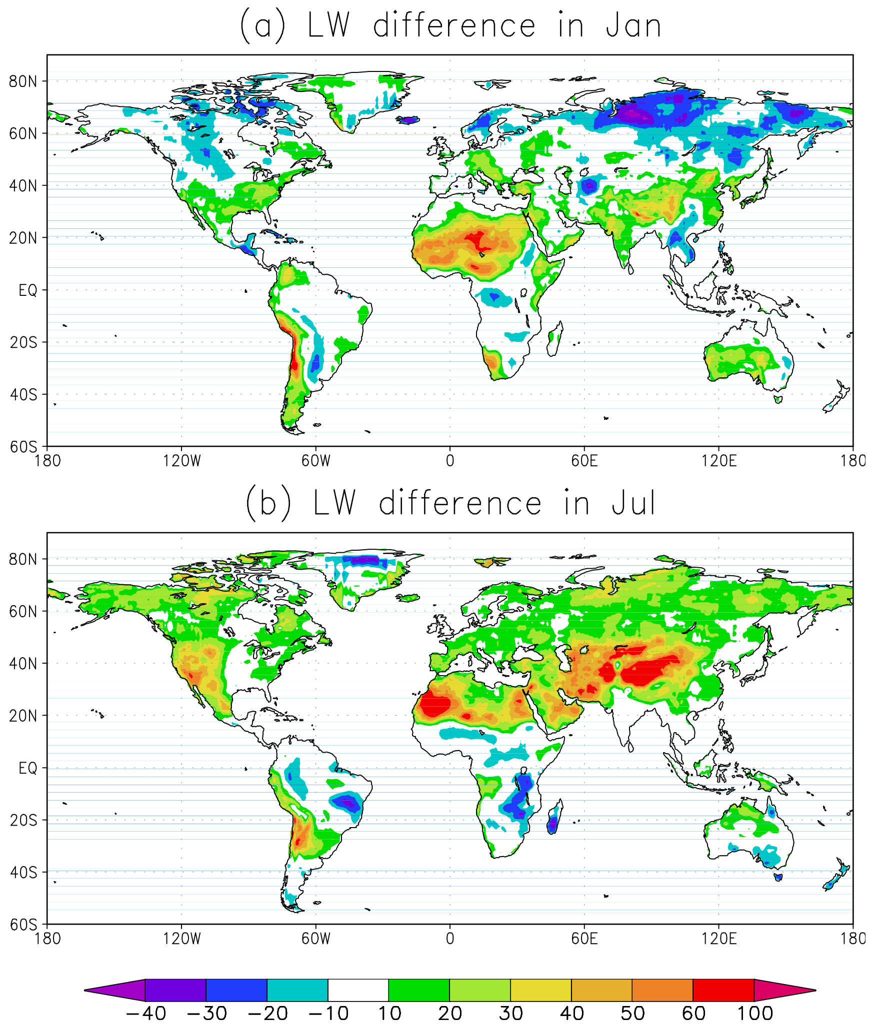

Figure 17 As in Figure 15, but for downward longwave radiation.